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(54) **PASSIVE PRELOAD AND CAPSTAN DRIVE FOR SURGICAL INSTRUMENTS**

(71) Applicant: **INTUITIVE SURGICAL OPERATIONS, INC.**, Sunnyvale, CA (US)

(72) Inventor: **Giuseppe Maria Prisco**, Calci Pisa (IT)

(73) Assignee: **INTUITIVE SURGICAL OPERATIONS, INC.**, Sunnyvale, CA (US)

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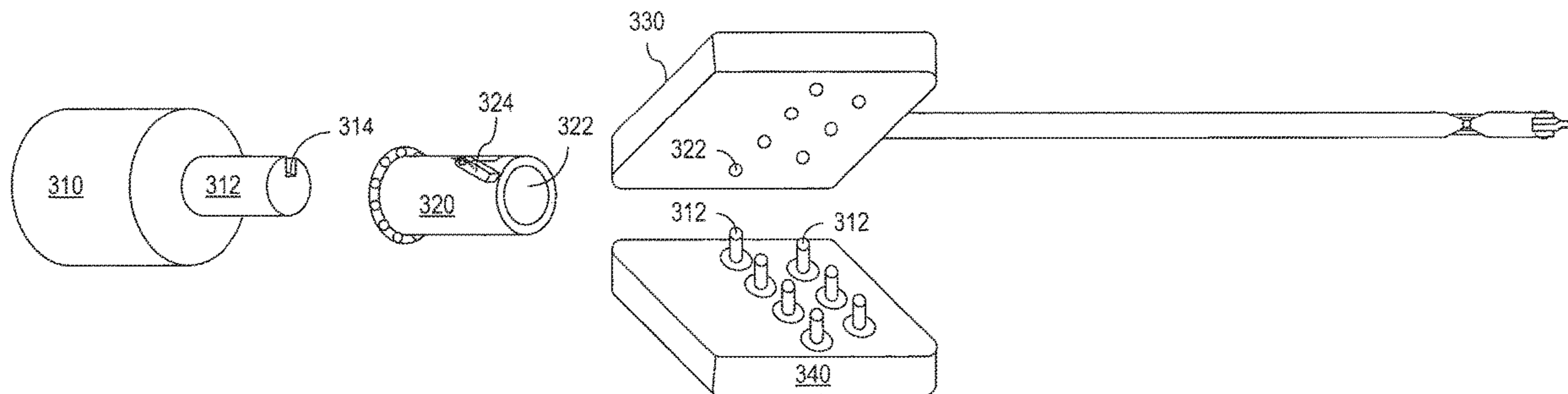
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Primary Examiner — Ahmed M Farah
Assistant Examiner — Jonathan T Kuo
(74) *Attorney, Agent, or Firm* — Haynes and Boone, LLP.

(57) **ABSTRACT**
A system comprises a medical instrument including a rotatable capstan. The rotatable capstan includes a capstan coupling member that can engage with a drive shaft coupling member such that rotation of the drive shaft causes rotation of the capstan about a drive axis concentric with the drive shaft, and can disengage from the drive shaft coupling member such that rotation of the drive shaft does not cause rotation of the capstan.

20 Claims, 4 Drawing Sheets



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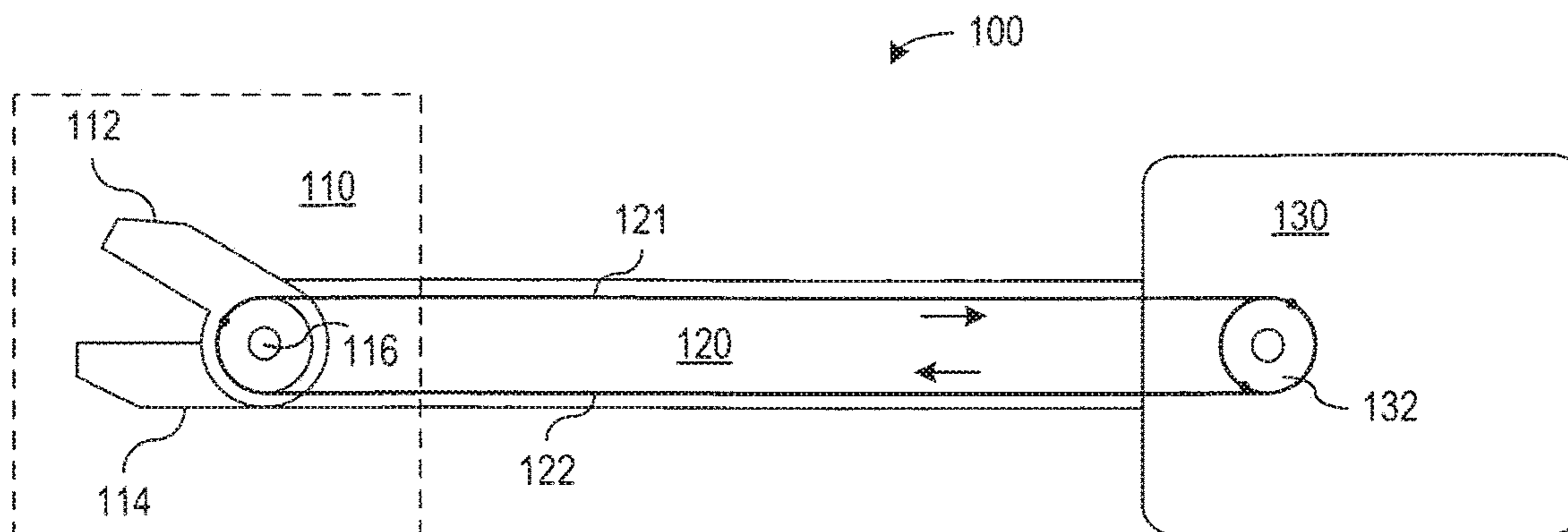


FIG. 1 (PRIOR ART)

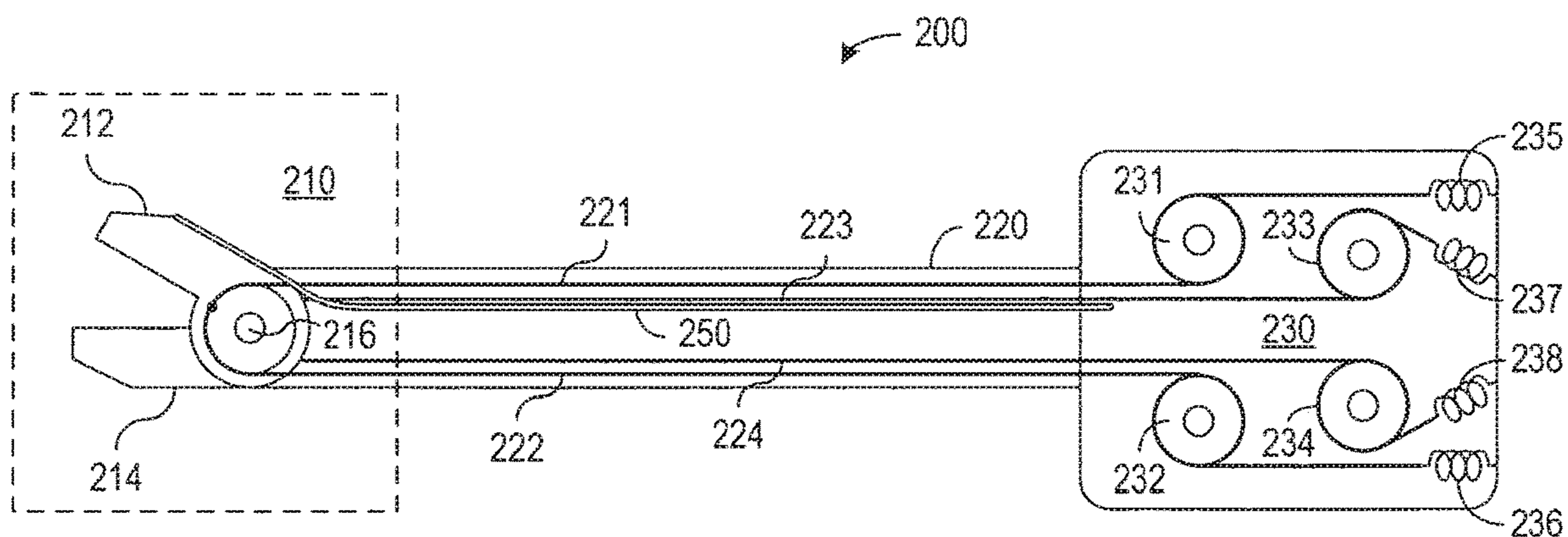


FIG. 2A

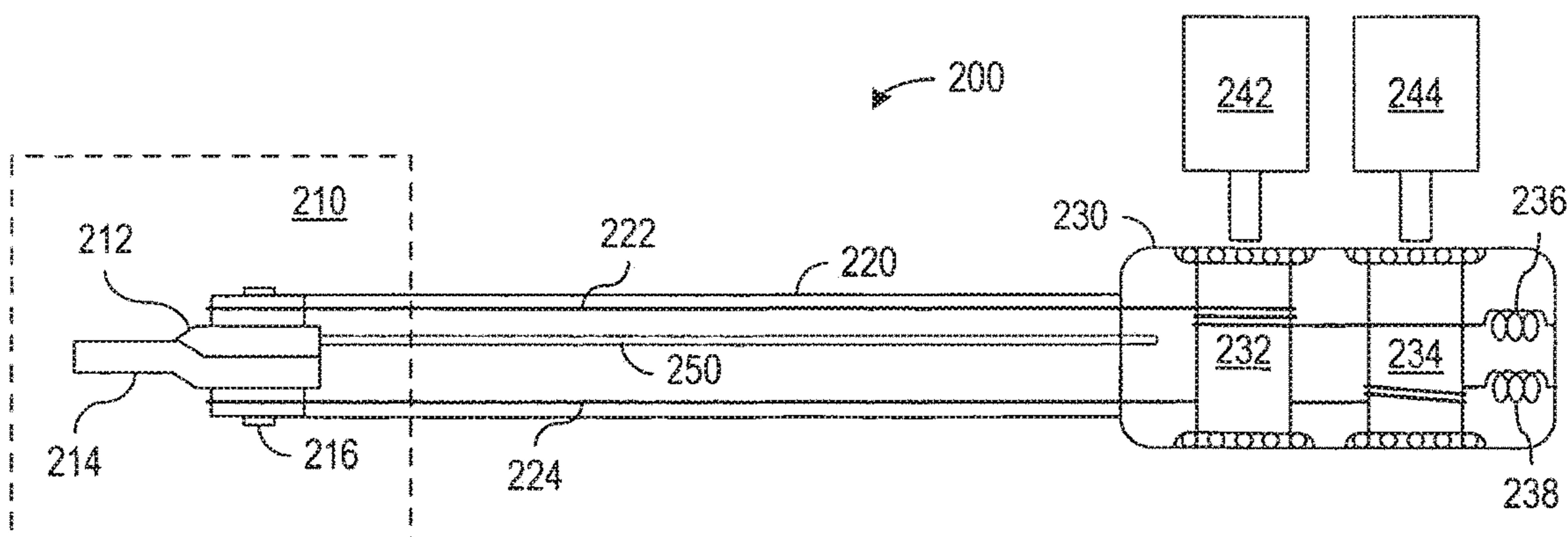


FIG. 2B

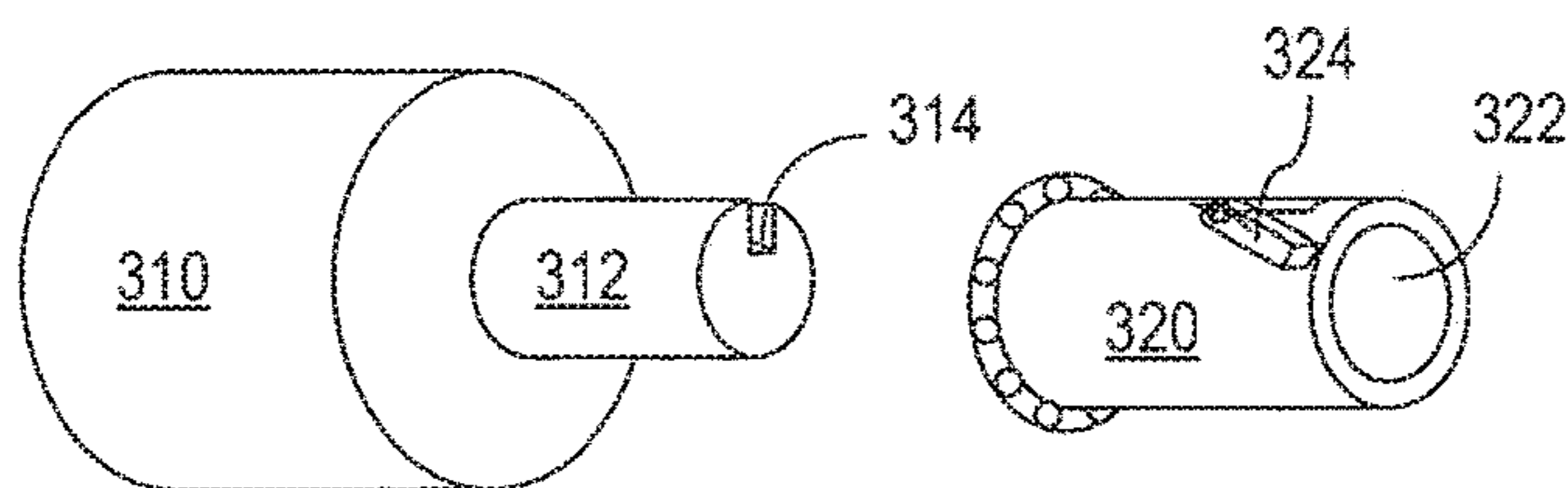


FIG. 3A

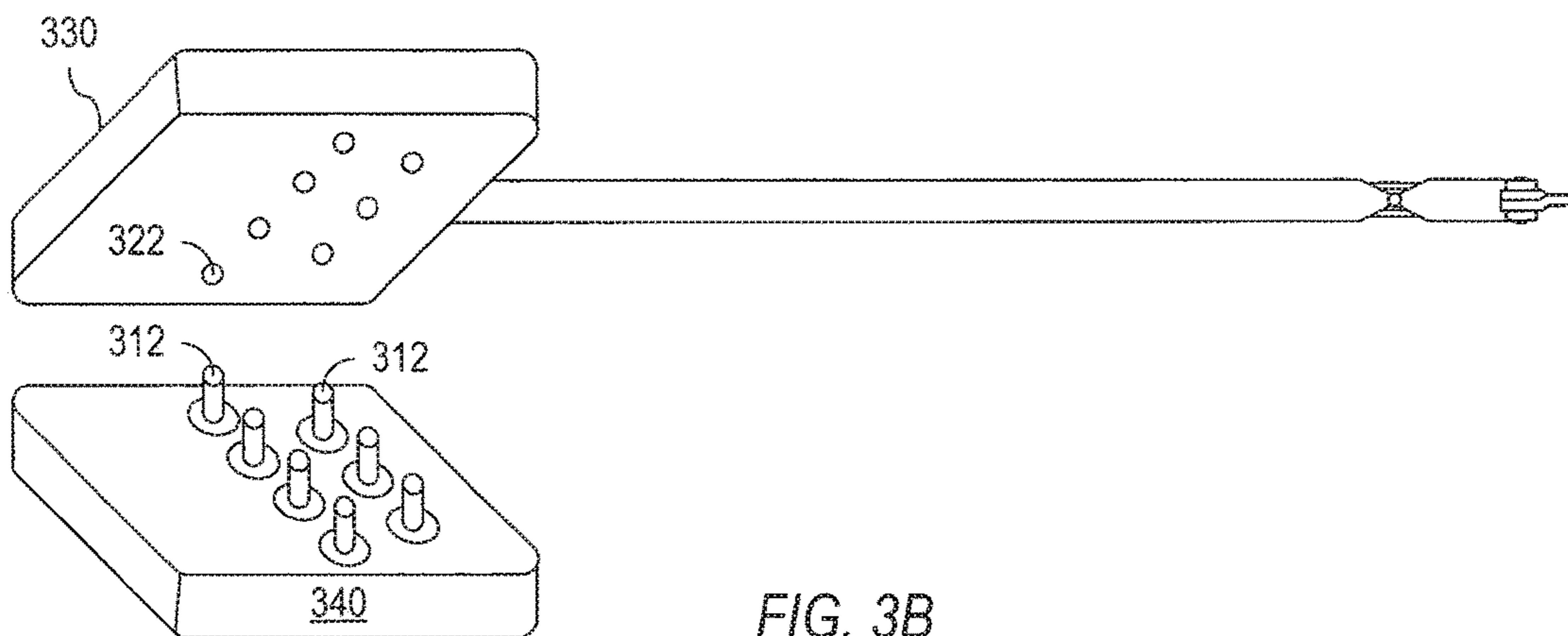


FIG. 3B

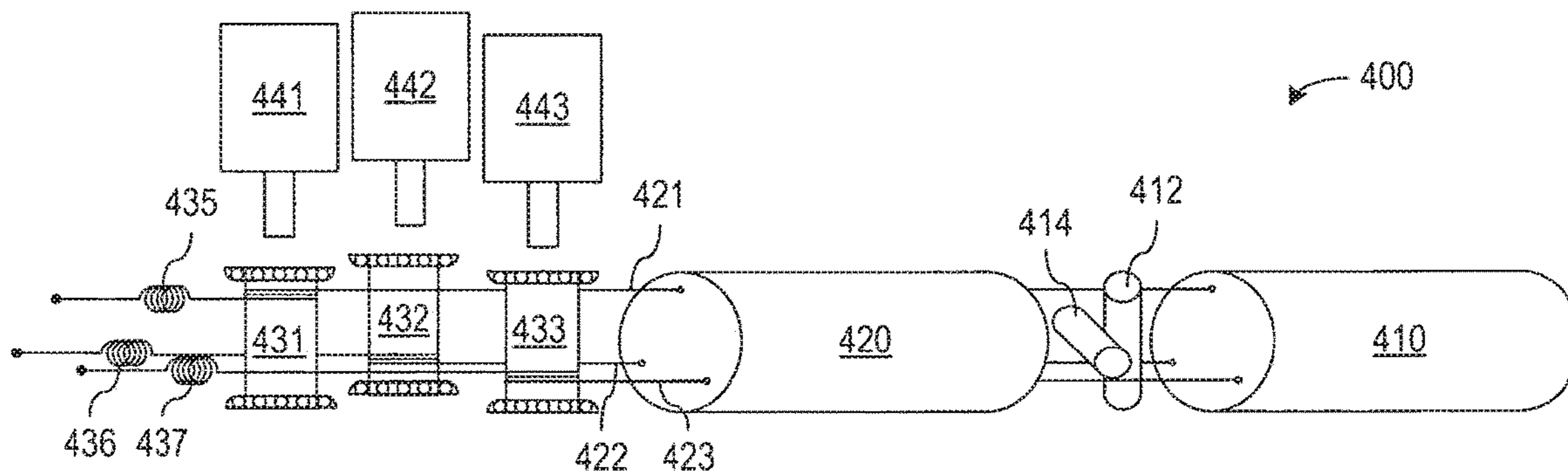


FIG. 4

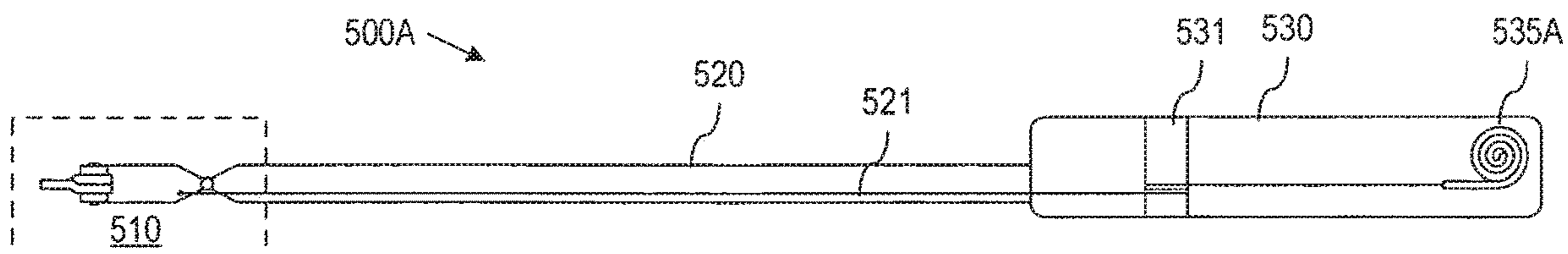
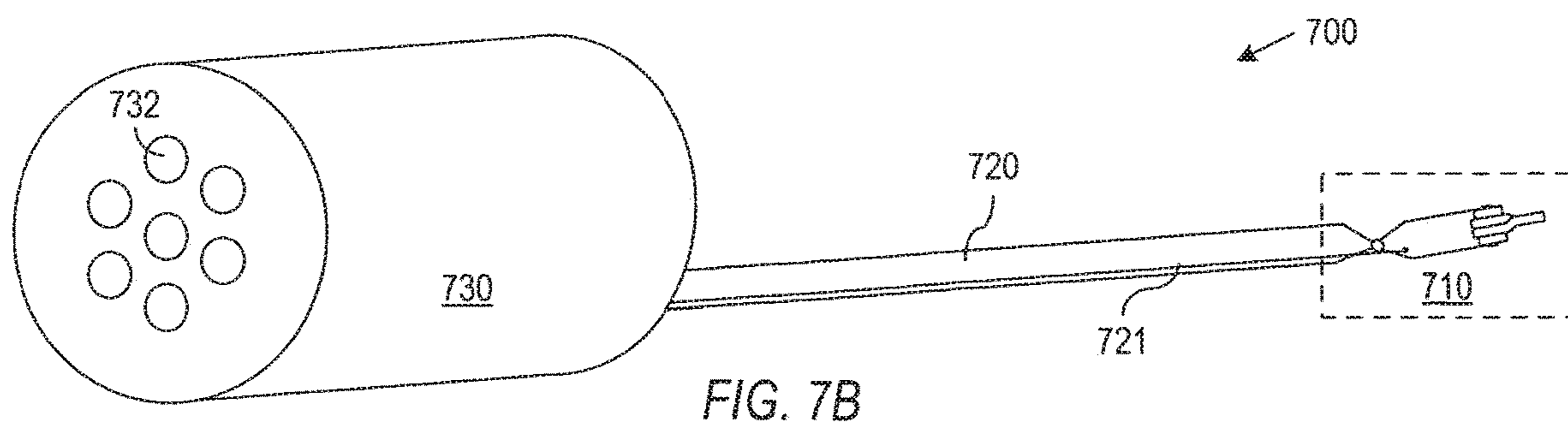
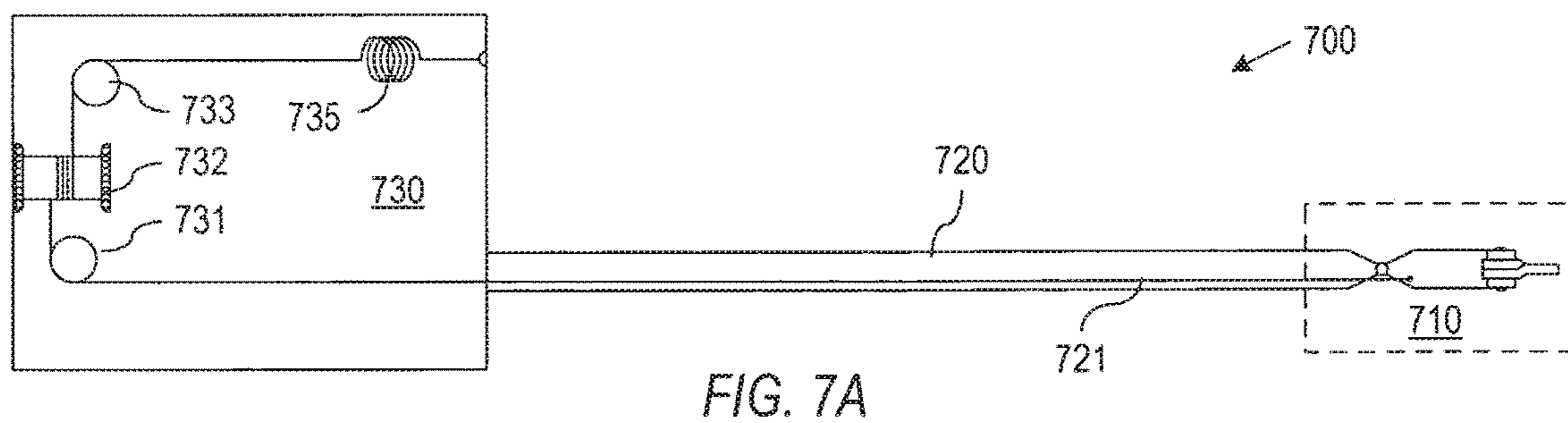
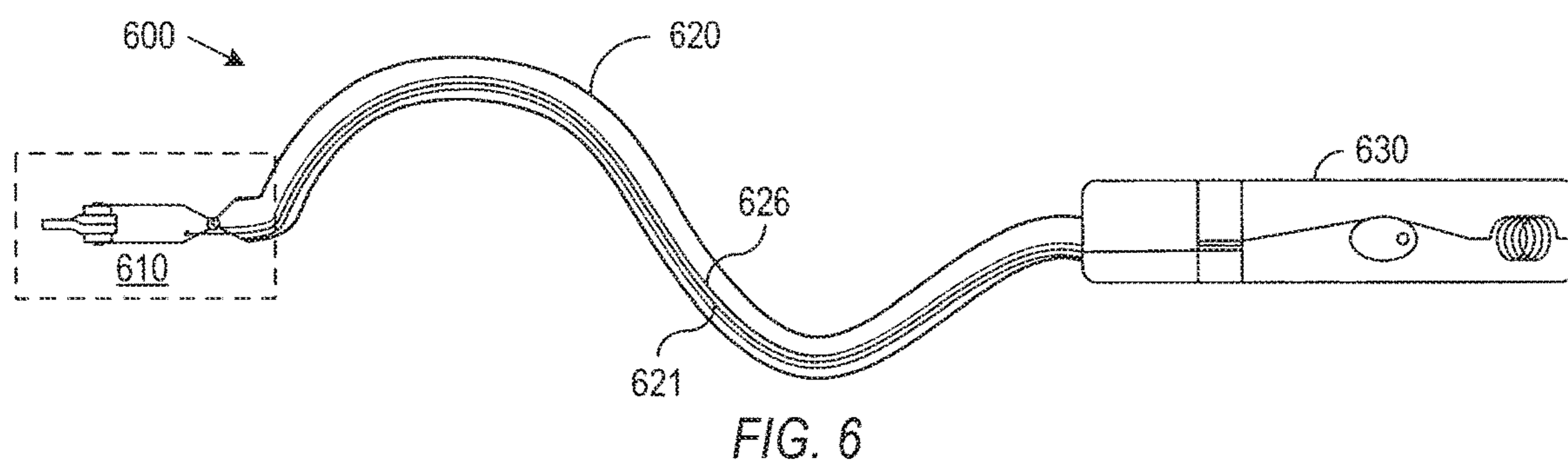
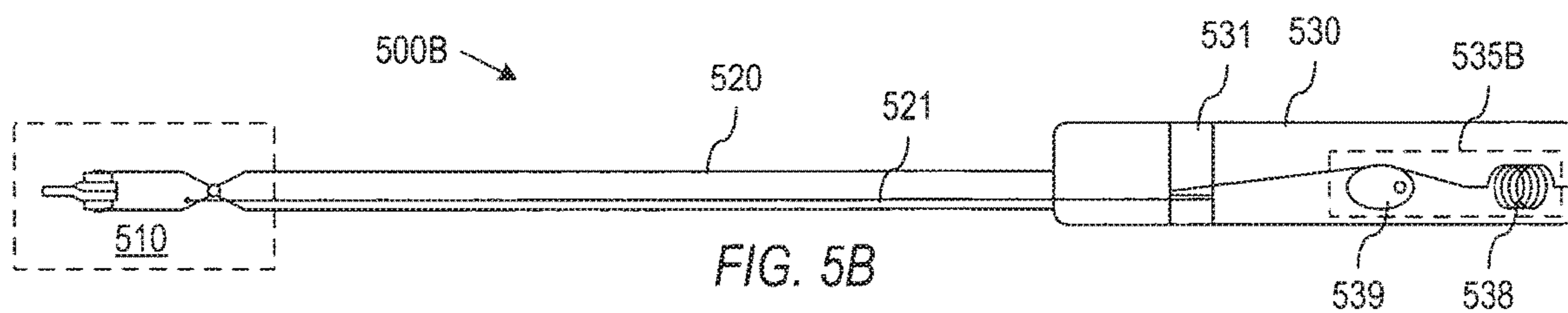


FIG. 5A



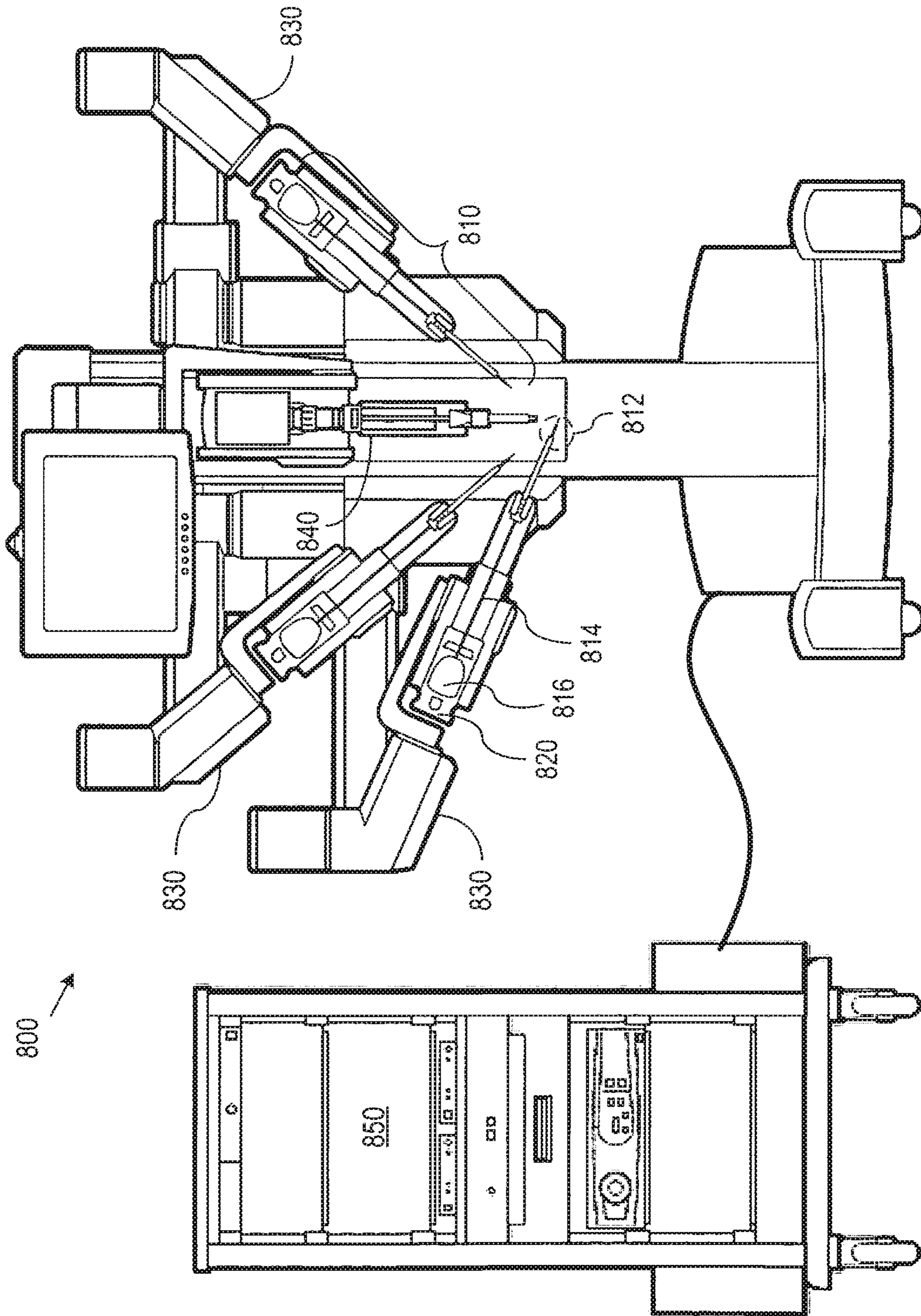


FIG. 8

**PASSIVE PRELOAD AND CAPSTAN DRIVE
FOR SURGICAL INSTRUMENTS**

CROSS-REFERENCE TO RELATED
APPLICATIONS

This application is a continuation application of U.S. application Ser. No. 15/001,948, filed Jan. 20, 2016, which is a continuation application of U.S. application Ser. No. 12/286,644, filed Sep. 30, 2008, and issued as U.S. Pat. No. 9,259,274, filed Sep. 30, 2008 on Feb. 16, 2016, both of which are incorporated herein by reference in its entirety their entireties.

BACKGROUND

Robotically (as used herein, the terms “robot” or “robotically” and the like include teleoperation or telerobotic aspects) controlled instruments are well known and often used in minimally invasive medical procedures. FIG. 1 shows an example of an instrument **100** having a structure that is simplified to illustrate basic working principles of some current robotically controlled medical instruments. Instrument **100** includes a tool or end effector **110** at the distal end of a shaft **120**. The proximal end of shaft **120** attaches to a transmission or drive mechanism **130** that is sometimes referred to as backend mechanism **130**. During a medical procedure, end effector **110** and the distal end of shaft **120** can be inserted through a small incision or a natural orifice of a patient to position end effector **110** at a work site in the patient. End effector **110** as illustrated includes jaws **112** and **114** that may be used at the work site for clamping, gripping, cutting, or other purposes. Other types of end effectors, for example, scalpels, wire loops, and cauterizing instruments, are known and could alternatively be mounted on the distal end of shaft **120**. Normally, a surgical instrument would further include a wrist mechanism (not shown) at the distal end of shaft **120** to provide additional degrees of freedom of motion for positioning, orienting, and using end effector **110**.

Tendons **121** and **122**, which may be stranded cables, rods, tubes, or similar structures, run from backend mechanism **130** through shaft **120** and attach to end effector **110**. A typical surgical instrument would also include additional tendons (not shown) that connect backend mechanism **130** to other structural members of end effector **110** or of a wrist mechanism, so that backend mechanism **130** can manipulate the tendons to operate end effector **110** and/or the wrist mechanism when performing the desired procedure at the work site. FIG. 1 illustrates two tendons **121** and **122** attached to jaw **112** in a pin joint structure, where jaw **112** is mounted for rotation about a pivot pin **116**. To enable both clockwise and counterclockwise rotations of jaw **112**, tendon **121** acts on jaw **112** at a moment arm about pivot pin **116** such that pulling on tendon **121** causes a torque tending to rotate jaw **112** clockwise in the view of FIG. 1. Similarly, tendon **122** acts at a moment arm such that pulling on tendon **122** causes a torque tending to rotate jaw **112** counterclockwise in the view of FIG. 1. Jaw **112** is thus provided with bi-directional actuation through pulling in a length of one tendon **121** or **122** and simultaneously releasing an identical length of the other tendon **122** or **121**. Mechanisms other than pin joints are known or can be devised that provide bi-directional actuation of a distal joint through pulling in a length of one tendon **121** or **122** and releasing an equal and opposite length of the other tendon **122** or **121**. For example, U.S. Pat. No. 6,817,974 (filed Jun. 28, 2002) entitled “Sur-

gical Tool Having Positively Positionable Tendon-Actuated Multi-Disk. Wrist Support” by Cooper et al. and U.S. Pat. No. 6,394,998 (filed Sep. 17, 1999) entitled “Surgical Tools For Use In Minimally Invasive Telesurgical Applications” by Wallace et al., both of which are incorporated herein by reference, describe some known medical instrument structures in which actuation requires pulling one or more tendons while releasing lengths of one or more other tendons.

Slack in tendons **121** and **122** can cause malfunctions, for example, by permitting tendons **121** and **122** to derail from guides or pulleys (not shown) that route tendons **121** and **122** through instrument **100**. Slack can also cause jumpy or unpredictable motion of the instrument. To avoid creating slack in tendon **121** or **122** when moving jaw **112**, backend mechanism **130** operates to release a length of one tendon **121** or **122** while simultaneously reeling in an equal length of the other tendon **122** or **121**. Tendons **121** and **122** can be attached to the same capstan **132** but wrapped in opposite directions to provide the desired movements of tendons **121** and **122** when a drive motor (not shown) turns capstan **132**. In cases where an end effector has several degrees of freedom that are controlled by several tendons, for instance as described in U.S. Pat. Nos. 6,394,998 and 6,817,974, the backend mechanism can include mechanisms other than capstans to perform the function of releasing and reeling in related lengths of tendons in order to avoid slack in the tendons as distal joints are turned. It can be seen that tendons **121** and **122** can be two separate components, or they may be part of a closed loop component with a capstan actuator, such as that disclosed in U.S. Pat. No. 7,316,681 B2 (filed Oct. 4, 2005) entitled “Articulated Surgical Instrument For Performing Minimally Invasive Surgery With Enhanced Dexterity And Sensitivity” by Madhani et al., which is incorporated herein by reference.

Avoiding slack may also require tendons **121** and **122** to be pre-tensioned, particularly when end effector **110** may be used for pushing and pulling, clamping, gripping, or other actions that encounter resistance. In particular, backend mechanism **130** can apply tension to tendon **122** to cause jaw **112** to clamp down on material between jaws **112** and **114**. Increasing tension in tendon **122** causes higher clamping force but also causes tendon **122** to stretch. To prevent the stretching of tendon **122** from causing a corresponding amount of slack in tendon **121**, tendon **121** can be preloaded with a tension that stretches tendon **121**. For example, assuming tendons **121** and **122** are identical, tendon **121** can be pre-loaded with a tension about equal to or greater than maximum clamping tension used in tendon **122**. As a result, tendon **121** starts stretched by the preloaded tension, and when applying a clamping force, the stretching of tendon **122** reduces the tension in tendon **121**, allowing tendon **121** to contract without becoming slack.

The tensions preloaded in tendons can increase the forces that a backend mechanism must apply to operate an instrument. In particular, tension increases friction where tendons may ride on guides or solid surfaces. Also, if shaft **120** is a flexible tube such as might be employed to follow a natural lumen in a patient’s body, the preloaded tension causes friction where tendons **121** and **122** contact curved surfaces of shaft **120**. In all the above cases, increased friction quickly makes accurate control of the motion of end effector **110** difficult and can lead to, imprecise manipulation of, e.g., tissue, sutures, and needles during a surgical procedure. Further, preloading of the correct tension in tendons of a medical instrument can also increase the complexity of the manufacturing process of the medical instrument. Accord-

ingly, medical instruments are desired that can avoid slack in drive tendons without requiring high preloaded tension.

SUMMARY

In accordance with an aspect of the invention, a passive preload system, such as a spring based mechanism, is attached to a tendon that is wrapped around a capstan, so that the passive preload system can control the relaxed tension in the tendon. The capstan can be driven by a motor when the tendon is needed to pull on a structural member of the instrument. For example, when applying clamping pressure or moving the structural member against resistance, capstan friction can produce tensions in the tendon that are many times the passive preload tension. However, when the tendon is not needed to apply force to the member, the capstan can be effectively and quickly made free to spin by zeroing or releasing the torque applied to the capstan by a drive motor, so that the passive preload system controls tendon tension and can provide just enough tension to prevent derailment or other malfunctions of the tendon. It should be noted that when the capstan is freed, the tendon can easily slide on the capstan since the tendon is not permanently attached to the capstan. In other words, forces are exchanged between the capstan and the tendon solely through friction. The reduced tension in relaxed tendons can reduce tendon friction, particularly in instruments with bent or flexible shafts. Two modes of operation of an instrument using a tendon attached to a passive preload system includes a mode where a motor turns a capstan about which the tendon is wrapped and thereby pulls on the tendon, and a mode where the capstan is freed and the tendon tension matches a tension of the passive preload system. A system can quickly switch between these two modes of operation by controlling the torque output by a drive motor and thus has a large bandwidth torque control.

One specific embodiment of the invention is a surgical instrument. The surgical instrument includes a shaft, a member mounted at a distal end of the shaft, a mechanism attached to a proximal end of the shaft, and a tendon. The member can be a link, or a jaw of an end effector, or a group of links coupled together, and the member is mounted to permit movement of the member relative to the shaft. The mechanism includes a capstan and a passive preload system, such as a spring system. The capstan can normally be free to roll and has a coupling through which a motor can attach to and rotate the capstan. The tendon has a first end attached to the member, runs down the shaft, wraps around the capstan, and has a second end attached to the passive preload system, which controls relaxed tension in the tendon.

Another specific embodiment of the invention is a robotic surgical system. The robotic surgical system includes a motor and an instrument coupled to the motor by means of a docking port. The robotic surgical system can also include an articulated arm holding the motor pack and the docking port. The instrument generally includes a shaft; a member mounted at a distal end of the shaft, a backend mechanism attached to a proximal end of the shaft, and a tendon. The member is mounted to permit movement of the member relative to the shaft. The backend mechanism includes a capstan and a passive preload system. The capstan is coupled to a drive motor in the docking port, so that the drive motor can rotate the capstan. The tendon has a first end attached to the member, runs down the shaft, wraps around the capstan, and has a second end attached to the passive preload system.

Yet another embodiment of the invention is a method for operating a surgical instrument containing a movable member, a first tendon attached for movement of the member in one direction, and a second tendon attached for movement of the member in another direction. The method includes: applying a torque to a first capstan about which a first tendon is wrapped; and at the same time, freeing from motor torques a second capstan about which the second tendon is wrapped so that a passive preload system attached to an end of the second tendon extending from the second capstan controls tension in the second tendon.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 shows a simplified version of a conventional robotically controlled medical instrument.

FIGS. 2A and 2B show a medical instrument in accordance with an embodiment of the invention using a spring and capstan friction to maintain a minimum tendon tension in the instrument.

FIG. 3A shows a system in accordance with an embodiment of the invention that couples a drive motor to a capstan.

FIG. 3B shows a system in accordance with an embodiment of the invention in which capstans for multiple tendons engage a motor pack.

FIG. 4 is an expanded view schematically illustrating an embodiment of the invention using three capstans to control an instrument wrist or joint having two degrees of freedom corresponding to rotations about two perpendicular axes.

FIGS. 5A and 5B show embodiments of the invention employing constant-force spring systems to maintain constant tendon tension in relaxed tendons.

FIG. 6 shows a medical instrument in accordance with an embodiment of the invention having an effect or at the distal end of a flexible shaft.

FIGS. 7A and 7B show side and perspective views of a medical instrument in accordance with an embodiment of the invention using drive motors with shafts parallel to the shaft of the instrument.

FIG. 8 shows a robotically controlled system in which medical instruments in accordance with embodiments of the present invention can be mounted for performance of medical procedures.

Use of the same reference symbols in different figures indicates similar or identical items.

DETAILED DESCRIPTION

In accordance with an aspect of the invention, a surgical instrument can avoid tendon slack and maintain a relatively low tension in a relaxed drive tendon by wrapping the tendon around a capstan that is allowed to rotate freely and attaching an end of the tendon to a passive preload system such as a spring system. When operating the surgical instrument, friction between the tendon and the capstan allows a drive motor that turns the capstan to reel in a length of the tendon, and capstan friction can apply a maximum tension to the tendon that depends exponentially on the total angle of wrap the tendon about the capstan. The force from the passive preload system, e.g., spring force from a spring, and the tension in a relaxed tendon can therefore be kept relatively low while still being able to produce the high tensions needed for clamping or other movement of the instrument against resistance. When the motor torque on the capstan is zeroed, the capstan can rotate freely, and the passive preload system can pull in the tendon and prevent the tendon from becoming slack. The low relaxed tensions

can decrease the forces needed for manipulation of the instrument, and tendon friction, which can be particularly problematic in medical instruments with curved or flexible shafts, can be reduced.

FIGS. 2A and 2B respectively show top and side views of a surgical instrument **200** in accordance with an embodiment of the invention. Instrument **200** includes an end effector **210** at a distal end of a shaft **220**, which is connected to a backend mechanism **230**. End effector **210** in the illustrated embodiment includes jaws **212** and **214**, which are both mounted to enable relative movement of jaws **212** and **214**. Jaws **212** and **214** can have shapes selected for the particular procedures for which effector **210** is intended. For example, jaws can be shaped to act as forceps of any desired type or could include blades that allow effector **210** to act as scissors. The materials and structure of jaws **212** and **214** can generally be selected for the particular uses of instrument **200**, and many suitable effector architectures are known or may be developed.

Jaw **212** is connected to a first pair of tendons **221** and **222**, and jaw **214** is connected to a second pair of tendons **223** and **224**. Each pair of tendons **221** and **222** or **223** and **224** may be portions of a continuous tendon having a point that is attached to jaw **212** or **214**, for example, by an adhesive or by a crimp residing in a notch in jaw **212** or **214**. In a typical embodiment, additional tendons (not shown) would be connected in instrument **200** to a wrist mechanism or joints (not shown) that provide additional degrees of freedom for movement for positioning and orienting end effector **210**.

Tendons **221**, **222**, **223**, and **224** apply force and torques to jaws **212** and **214** when pulled by backend mechanism **230** and can have any structure suitable for that task. For example, tendons can be stranded cables, wires, rods, or tubes made of metal, a polymer, or other material. In an exemplary embodiment, tendons **221**, **222**, **223**, and **224** include portions of stranded cable that are fused to tubes, with the stranded cable being used where significant bending or flexing of the tendons is expected, and the tubes being used elsewhere to reduce stretching of the tendons. In another embodiment, particularly useful when shaft **220** is flexible, tendons **221**, **222**, **223**, and **224** can be made of a woven polymer material and run inside individual sheaths (not shown).

FIGS. 2A and 2B illustrate the example embodiment where tendons **221**, **222**, **223**, and **224** attach to a pivot joint structure in which relative motion of jaws **212** and **214** corresponds to independent rotations of jaws **212** and **214** about a pivot pin **216**. This joint structure is only an example, and other mechanisms for moving members of a surgical instrument in response to tensions applied to tendons **221**, **222**, **223**, and **224** are known and could be employed in alternative embodiments of the invention. For example, a planar, cylindrical, or spherical rolling joint could provide similar freedom of motion to jaws **212** and **214** in end effector **210**, or a prismatic linear joint or slide could be employed in end effector **210** to provide a linear bidirectional degree of freedom of motion.

Shaft **220** is a hollow tube through which tendons **221**, **222**, **223**, and **224** run. Shaft **220** may be rigid or flexible. For example, shaft **220** may be a rigid stainless steel tube if instrument **200** is intended to be inserted through a straight cannula during a medical procedure, but shaft **220** would need to be flexible if instrument **200** is intended to follow the variable path of natural lumens. In a typical configuration, shaft **220** may have a diameter of about 5 mm or 8 mm for use with some existing cannulae and may have a length on

the order of several tens of centimeters. In case the shaft **220** is flexible, the tendons can run inside sheaths in a Bowden cable arrangement (i.e., like bicycle cables). As used herein, the term “flexible” includes continuously flexible components (such as a rubber tube, which bends at each point along its length) and constrained series of short, discrete links that allow the links to approximate the movement of a continuously flexible unit (such as a series “snake-like” vertebrae).

Backend mechanism **230** attaches to the proximal end of shaft **220** and acts as a transmission that converts the rotation of drive motors (e.g., drive motors **242** and **244** in FIG. 2B) into movement of end effector **210**. Backend mechanism **230** particularly manipulates tendons **221**, **222**, **223**, and **224** to operate end effector **210** and may additionally be able to rotate or move shaft **220** to change the orientation or position of end effector **210**. In the illustrated embodiment, backend mechanism **230** includes one capstan **231**, **232**, **233**, or **234** per tendon **221**, **222**, **223**, or **224**. In accordance with an aspect of the current invention, each tendon **221**, **222**, **223**, or **224** wraps for a set wrapping angle (that could be less than a full turn or as large as one or more turns) around the corresponding capstan **231**, **232**, **233**, or **234** and has an end extending from the capstan **231**, **232**, **233**, or **234**. Tendons **221**, **222**, **223**, and **224** are not required to be permanently attached to capstans **231**, **232**, **233**, and **234** and may be able to slip relative to the capstans **231**, **232**, **233**, and **234**.

The ends of tendons **221**, **222**, **223**, and **224** attach to passive preload systems, here implemented as linear coiled springs **235**, **236**, **237**, and **238**, which can be anchored to a case or chassis of backend mechanism **230**. Springs **235**, **236**, **237**, and **238** are biased, e.g., stretched, so that springs **235**, **236**, **237**, and **238** apply a non-zero force to respective attached tendons **221**, **222**, **223**, and **224** throughout the range of motion of surgical instrument **200**. With this configuration, when capstans **231**, **232**, **233**, and **234** are free to rotate, the corresponding spring **235**, **236**, **237**, or **238** controls the tension in the associated tendon **231**, **232**, **233**, or **234** and avoids slack by pulling in the required length of tendon **231**, **232**, **233**, or **234**. Tendons **221**, **222**, **223**, and **224** do not require a preloaded tension that is higher than the maximum tensions used for operation of surgical instrument **200**.

Each passive preload system more generally can be any structure or system that is able to apply a force to the free end of a tendon while allowing the tendon end to displace. The preload system is passive in that the system does not need to respond to a control or feedback system. Such systems can use linear coil springs as illustrated in FIGS. 2A and 2B or use other spring elements, such as rotary coil springs, leaf springs or compliant members, such as bending beams, cantilever beams, or elastic bands. Further, the spring elements or compliant members can work through extension or compression to apply force directly or indirectly to the end of the attached tendons. Other methods for applying the desired force, such as a system using weights or magnets, might alternatively be employed. In addition to the source of force, the passive preload system may include mechanical elements that direct or control the magnitude of the force applied to the attached tendon.

End effector **210** can be operated using drive motors which are under the active control of human input (e.g., master control input in a master-slave servo control system) and software executed in a robotically controlled system. In particular, four drive motors, which are provided in a docking port of a control system (not shown), can be respectively coupled to capstans **231**, **232**, **233**, and **234** of FIG. 2A. FIG. 2B shows two drive motors **242** and **244**,

which are coupled to capstans **232** and **234**. The orientations of capstans **231**, **232**, **233**, and **234** in backend mechanism **230** are not required to have particular fixed relations to the position or configuration of instrument **200**. Accordingly, any mechanical coupling that allows a motor to rotate or apply a torque to a capstan can be used for the coupling of motors **242** and **244** to capstans **232** and **234** in backend mechanism **230**.

Backend mechanism **230** can be removably attached to a motor pack including motors **242** and **244** through a sterile barrier, such as a sterile sheet of plastic, and the instrument **200** can be designed to be disposable or reusable and sterilizable. When the instrument is detached from the motor pack, the passive preload systems (e.g., springs **235**, **236**, **237**, and **238** in FIG. 2A) still keep tendons **221**, **222**, **223**, and **224** from slacking and allow end effector **210** and shaft **220** (when flexible) to be manually arranged (or posed) in any configuration without damaging backend mechanism **230** or creating slack in any tendons **221**, **222**, **223**, or **224**. This “backdriving” capability is generally a desirable property of a surgical instrument, particularly an instrument with a flexible shaft that may be bent or manipulated during instrument insertion while the instrument is not under active control. For example, the flexible shaft can be manually posed, and the tendons within the shaft do not experience undue tension or slack.

One system for mechanically coupling a motor to a capstan uses a friction connection where a pinion of the motor fits tightly into a bore in the capstan and relies on friction between the pinion and bore. Generally, when the motor rotates the capstan, the tendon wrapped around the capstan will tighten, which can increase the frictional connection when the capstan is sufficiently elastic to shrink in radius in response to the squeezing force from the tendons. FIG. 3A shows an alternative technique for mechanically coupling a drive motor **310** to a capstan **320**. With this particular technique, a shaft **312** of drive motor **310** fits into a bore **322** of capstan **320**. Shaft **312** has a slot **314**, and capstan **320** has a spring loaded lever or other projection **324** that extends into bore **322**. Projection **324** can be compressed when shaft **312** is inserted in bore **322**, but projection **324** can spring back and engage slot **314** when slot **314** is rotated to become aligned with projection **324**. Motor **310** can thus apply a torque to capstan **320**. It should be understood that in other implementations, male-female mechanical relationships and their many variations can be reversed (e.g., so that a projection extends from the motor shaft and engages a slot in the capstan).

Backdriving capabilities of an instrument can also create situations where the orientation of capstan **320** relative to shaft **312** may be unknown when shaft **312** is inserted into bore **322**. Regardless of the relative orientation, with the mechanical coupling of FIG. 3A, motor **312** can simply rotate shaft **312** until projection **324** engages slot **314**. This ability is particularly important when a backend mechanism **330** includes multiple capstans arranged in an array to engage shafts **312** of motors in a motor pack **340** as illustrated in FIG. 3B, where all of the motor shafts **312** may have different and unknown orientations relative to the bores **322** of associated capstans.

The drive motors coupled to backend mechanism **230** of FIGS. 2A and 2B are generally operated to either apply a torque to the associated capstan or to allow the associated capstan to turn freely. In a process that controls a pair of tendons that are connected for rotation of a structural member of instrument **200**, one drive motor applies a torque to a capstan around which one tendon is wrapped, and the

capstan about which the other tendon is wrapped is allowed to freely rotate. For example, to rotate jaw **212** counterclockwise in the view of FIG. 2A, motor **242**, which engages capstan **232**, is activated and turns capstan **232** in a direction that pulls on tendon **222**. The resulting torque that tendon **222** applies to jaw **212** tends to rotate jaw **212** counterclockwise toward jaw **214**. The maximum tension that capstan **232** can apply to tendon **222** without tendon **222** slipping on capstan **232** is proportional to the force from spring **236** and increases exponentially with the wrap angle of tendon **222** about capstan **232**. Accordingly, with a suitable wrap angle for tendon **222** about capstan **232**, the force from spring **236** can be much less than the maximum tension that may need to be applied to tendon **222** when rotating jaw **212** against resistance. While capstan **232** pulls in tendon **222**, capstan **231** is free to rotate and pays out a length of tendon **221** corresponding to the rotation of jaw **212**. Capstan **221** being free to rotate allows the tension in the portion of tendon **212** between capstan **231** and jaw **212** to equalize with the tension in the portion of tendon **221** between capstan **231** and spring **235**. Tendon **221** does not become slack, and the tension in tendon **221**, which is controlled by spring **235**, can be kept much lower than the maximum anticipated tension applied to tendon **222**. When jaw **212** reaches the desired position and no clamping tension is required in tendon **222**, both capstans **231** and **232** can be released to rotate freely. Clockwise rotation of jaw **212** can be achieved through operation of a drive motor coupled to capstan **231** to pull on tendon **221** while capstan **232** is left free to rotate. Rotations of jaw **214**, or movements of other elements of instrument **200**, can also be performed using similar procedures.

The control of jaws **212** and **214** and any joint in end effector **210** or shaft **220** can be effected in a closed loop by basing the motor control torques for that joint on measurement of the current position of the joint. Such measurements can, for example, be done by using a sensing technology such as the one described in U.S. Pat. App. Pub. No. US 2007/0156019 A1 (filed Jul. 20, 2006), entitled “Robotic Surgery System Including Position Sensors Using Fiber Bragg Gratings” by Larkin et al., and U.S. patent application Ser. No. 12/164,829 (filed Jun. 30, 2008) entitled “Fiber optic shape sensor” by Prisco, both of which are incorporated herein by reference. FIGS. 2A and 2B illustrate an illustrative shape sensing fiber **250** that extends to jaw **212** for sensing of the position of jaw **212**. For the control loop, a control system compares a desired joint position with a measured joint position to compute a joint position error. A control or correction torque is then computed based on the current value of the joint position error, for instance using a Proportional Derivative Integral control law. Depending on the control torque sign indicating a clockwise or counterclockwise correction, one of the motors associated with the joint is commanded to apply a torque to its associated capstan while the other motor associated with the joint is commanded to zero its motor torque, thereby letting go of its associated capstan. In this way, the joint is placed in the desired position.

FIG. 4 illustrates portions of a medical instrument **400** in accordance with an embodiment of the invention using three tendons **421**, **422**, and **423** to control rotation of a structural member **410** about two perpendicular axes defined by pivots **412** and **414**. Member **420** may be a link in a wrist or joint mechanism in an instrument shaft or in an end effector. Most of the mechanical structure associated with the joint and pivots **412** and **414** is omitted to better illustrate the operation of tendons **421**, **422**, and **423**, but such joints can be implemented using known mechanical structures. Tendons

421, 422, and 423, which generally may be of the same type and construction as described above with reference to FIGS. 2A and 2B, attach to member 410 and extend back through a shaft 420 to a backend mechanism including capstans 431, 432, and 433 and passive preload systems 435, 436, and 437. Shaft 420 may generally be the same as shaft 220 described above. Also, in a manner similar to described above, each tendon 421, 422, or 423 wraps around a corresponding capstan 431, 432, or 433 and has an end attached to a corresponding passive preload system 435, 436, or 437. Passive preload systems 435, 436, and 437 can be anchored to the case or chassis of the backend mechanism.

Controlled rotation of member 410 about pivot 412 relies on tendons 421 and 422 being attached to member 410 at moment arms such that pulling tendon 421 or 422 can cause rotation of member 410 about pivot 412 in a direction that is opposite to the rotation that pulling on tendon 423 can cause. Similarly, rotation of member 410 about pivot 414 relies on tendons 422 and 423 being attached to member 410 at moment arms such that pulling tendon 422 or 423 can cause rotation of member 410 about pivot 414 in a direction that is opposite to the rotation that pulling on tendon 421 can cause. The desired relative anchoring of tendons 421, 422, and 423 can be achieved, for example, by terminating tendons 421, 422, and 423 on rays that extend at a 120° angles relative to each other from a central longitudinal axis of member 410. In operation of instrument 400, passive preload systems 435, 436, and 437 and drive motors 441, 442, and 443 create tensions in tendons 421, 422, and 423, and a control system (not shown) can control drive motors 441, 442, and 443 to balance the torques about pivots 412 and 414 as needed to achieve the desired relative orientation of member 410 or overcome resistance to the movement or stationary position of member 410. Sensors (not shown; see e.g., element 250 in FIGS. 2A and 2B) may be implanted in structural member 410 to provide feedback to the control system operating motors 441, 442, and 443. One illustrative example of a structural member 410 is a part of the parallel motion mechanism disclosed in U.S. Pat. App. Pub. No. US 2008/0065102 A1 (filed Jun. 13, 2007) entitled "Parallel Motion Mechanism" by Cooper, which is incorporated herein by reference.

The instruments described above employ passive preload systems to maintain a minimum relaxed tension in drive tendons. Passive preload systems as described above are readily implemented employing flexible members or springs, such as linear or rotational coil springs. Most common springs produce forces that are at least approximately described by Hooke's law over a range of forces and deflections. In particular, most springs apply a force that is proportional to the deflection of the spring from its equilibrium length. With Hooke's law springs, the tensions in relaxed tendons of an instrument of the types described above will depend on how far the springs are stretched, which in turn depends on the general configuration of the instrument, including the positions and orientations of the joints and effector in the instrument. This variation may not be significant if the range of motion of the tendons is small compared to the stretch already in the springs for biasing. However, simple Hooke's law springs will tend to create a minimal energy configuration for the instrument, and the instrument will tend to approach that configuration when all of the capstans are free to rotate. In practice, as mentioned above, this effect is small since the spring length change can be designed to be small compared to the spring bias. Further, spring systems that apply constant force can be used to avoid or reduce variations in the tensions in relaxed tendons.

FIG. 5A shows a surgical instrument 500A in accordance with an embodiment of the invention employing a constant-force spring 535A. Instrument 500A includes an end effector 510, a shaft 520, and a backend mechanism 530, all of which can be substantially the same as described for similar elements above. A tendon 521 attaches to end effector 510, extends back through shaft 520 to backend mechanism 530, wraps around a capstan 531, and attaches to constant-force spring 535A. A constant-force spring is a spring that exerts a constant force over the range of motion of the spring. In the embodiment of FIG. 5A, constant-force spring 535A is a rolled ribbon of spring material that is relaxed when the ribbon is fully rolled up. As the ribbon unrolls, the portion of the ribbon near the roll produces the spring force. This spring force remains nearly constant as the ribbon unrolls because the portion of the ribbon that produces the spring force, i.e., the portion near the roll, has nearly the same shape as the spring unrolls.

Constant-force spring systems can also be produced or approximated using a spring obeying Hooke's law and one or more cams or variable radius pulleys. FIG. 5B shows a surgical instrument 500B containing the same elements as in surgical instrument 500A, with the exception that constant-force spring 535A is replaced with a constant-force spring system 535B that includes a spring element 538 that obeys Hooke's law and a variable radius cam 539. In particular, cam 539 has an input radius that is different from its output radius, with the ratio of the input radius and the output radius being the cam force transmission ratio at the specific angular position of cam 539. As spring element 538 extends, the input force to cam 539 increases proportionally and cam 539 rotates. The cam profile is designed to reduce the cam force transmission ratio as cam 539 rotates an amount that cancels the increase in input spring force. The spring element 538 can also be implemented, for example, as a linear spring, a rotational spring, or a leaf spring or as a compliant member such as a cantilever beam or elastic band. In one particular embodiment, spring element 538 is a rotational spring that is integrated with the cam 539 on the same cam axis. More details on constant spring forces are described in U.S. Pat. App. Pub. No. US 2004/0035243 A1 (filed May 22, 2003) entitled "Counter Balance System And Method With One Or More Mechanical Arms" by Duval, which is incorporated herein by reference.

The low tension maintained using techniques described above are particularly advantageous in surgical instruments having flexible shafts. FIG. 6, for example, illustrates a medical instrument 600 having an end effector 610 on the distal end of a shaft 620 that is flexible and bent into a curved, sinuous shape. Such bending may result during a minimally invasive medical procedure when end effector 610 and shaft 620 are guided through a natural lumen, such as a portion of the digestive tract of a patient. The shape of shaft 620 will generally be different during different procedures. A tendon 621 used to operate end effector 610 runs through flexible shaft 620 and therefore follows almost the same path as shaft 620. Tendon 621 may have a surrounding sheath 626 that is more rigid than tendon 621 to aid in guiding tendon 621 through shaft 620 and prevent lateral movement of tendon 621 during actuation of effector 610. Bends in shaft 620 can cause tendon 621 to ride on the solid surface of sheath 626, and frictional forces at these bends increase with the tension in tendon 621. Accordingly, reducing the relaxed tension in tendon 621 when shaft 620 is bent can reduce the force that backend mechanism 630 must be able to exert to operate effector 610. Backend mechanism 630 may thus be able to use small components that may not

be robust enough to overcome the higher tendon friction that results from higher tendon tension.

The above-described embodiments illustrate embodiments of surgical instruments having backend mechanisms in which capstans have rotation axes that are generally perpendicular to the direction of the instruments' shafts. However, many mechanical systems for routing and directing tendons are known and could be employed in a backend mechanism to alter configuration of the capstans. FIG. 7A, for example, illustrates an embodiment of a medical instrument 700 having a backend mechanism 730 containing a capstan 723 that has a rotation axis parallel to a shaft 720 on which an end effector 710 is mounted. In this embodiment, a tendon 721 attached to end effector 710 runs the length of shaft 730 into backend mechanism 730. Tendon 721 then winds around a first cam or pulley 731, wraps around capstan 732, winds around a second cam or pulley 733 and attaches to a spring 735 that is anchored in backend mechanism 730. Cams or pulleys 731 and 733 may be shaped to provide a constant tension in tendon 721 when tendon 721 is relaxed, even if spring 735 obeys Hooke's law.

FIG. 7B shows that the bores of the capstans for multiple tendons in medical instrument 700 can be arranged on the back (most proximal surface) of backend mechanism 730. A docking port for instrument 700 can provide a matching array of motor shafts that fit into the bores of the capstans 732 for use of instrument 700 when instrument 700 is connected to the control system. As described above, many male-female mechanical mating configurations can be used, as well as many ways to rotationally align the capstans and motor shafts.

FIG. 8 shows an example of a robotically controlled system 800 capable of using medical instruments in accordance with embodiments of the present invention. System 800, which may, for example, be a da Vinci® Surgical System available from Intuitive Surgical, Inc. includes multiple surgical instruments 810, each of which is mounted in a docking port 820 on a robotic manipulator arm 830. Each instrument 810 generally includes an end effector 812, a shaft 814, and a backend mechanism 816, which may be of any of the types described above. In particular, instruments 810 may have shafts 816 that are rigid or flexible. When shafts 816 are flexible for insertion into and following of a natural lumen, robotically controlled and jointed arms 830 may not be needed, and instruments 810 can be mounted in mounting ports 820 on a cart or other fixed structure. Instruments 810 can be made interchangeable, so that the instruments 810 mounted in docking ports 820 can be selected for a particular medical procedure or changed during a medical procedure to provide the clinical functions needed. Instruments 810 can implement many functions, including but not limited to forceps or graspers, needle drivers, and scissors of many different shapes and sizes. An endoscopic camera, for example, a stereoscopic camera, can also be mounted on an arm 840 to provide visual information, particularly images, of the work site at which instruments 810 are operating.

Docking ports 820 generally include drive motors that provide mechanical power for operation of instruments 810 and systems for establishment of a sterile barrier between instrument 810 and the rest of robotically control system 800. Some suitable sterile barriers are described in U.S. Pat. No. 6,132,368 (filed Nov. 21, 1997) entitled "Multi-Component Telepresence System And Method" by Cooper, which is incorporated herein by reference. Docking ports 820 may additionally include an electrical interface for communication with instruments 810, for example, to iden-

tify the type of instrument in the docking port and to access parameters of the instrument. The electrical interface may also convey measurements such as measurements of the position and orientation of effectors 812 or shaft 814. A computer system 850 can receive the measurements and execute software that controls drive motors in the docking ports 820 as needed to manipulate instruments 810 as directed by a surgeon or other medical personnel using system 800 to perform a surgical procedure.

Although the invention has been described with reference to particular embodiments, the description is only an example of the invention's application and should not be taken as a limitation. Various other adaptations and combinations of features of the embodiments disclosed are within the scope of the invention as defined by the following claims.

What is claimed is:

1. A teleoperational instrument system, comprising:
 - a flexible tubular shaft having a proximal end and a distal end;
 - a mechanism coupled to the proximal end of the flexible tubular shaft, the mechanism comprising a plurality of capstans, each capstan including:
 - a bore sized for concentric engagement with a drive shaft of a respective drive motor configured to drive the capstan, and
 - a capstan coupling member adapted to engage with a drive shaft coupling member such that rotation of the drive shaft causes rotation of the capstan about a drive axis concentric with the bore and the drive shaft, and further adapted to disengage from the drive shaft coupling member such that rotation of the drive shaft does not cause rotation of the capstan; and
 - a plurality of tendons, each of the plurality of tendons including a proximal section coupled to one of the plurality of capstans and a distal section coupled to a member disposed at the distal end of the flexible tubular shaft.
2. The teleoperational instrument system of claim 1, wherein the capstan coupling member is a projection and the drive shaft coupling member is a slot.
3. The teleoperational instrument system of claim 1, wherein the drive shaft coupling member is a projection and the capstan coupling member is a slot.
4. The teleoperational instrument system of claim 1, wherein the plurality of capstans includes a plurality of rows of capstans.
5. The teleoperational instrument system of claim 1, wherein each capstan of the plurality of capstans has a single engaging orientation with respect to the drive shaft of the respective drive motor.
6. The teleoperational instrument system of claim 1, wherein each capstan of the plurality of capstans is arranged in parallel alignment with each of the other capstans in the plurality of capstans.
7. The teleoperational instrument system of claim 1, wherein each tendon of the plurality of tendons extends through a sheath inside the flexible tubular shaft.
8. The teleoperational instrument system of claim 1, wherein the drive axis is perpendicular to the proximal end of the flexible tubular shaft.
9. The teleoperational instrument system of claim 1, wherein the mechanism engages each respective drive motor through a sterile barrier.

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10. A teleoperational instrument assembly, comprising:
 a teleoperational manipulator including a plurality of drive motors;
 a flexible tubular shaft having a proximal end and a distal end;
 a mechanism coupled to the proximal end of the flexible tubular shaft, the mechanism comprising a plurality of capstans, each capstan including:
 a bore sized for concentric engagement with a drive shaft of a respective drive motor of the plurality of drive motors, and
 a capstan coupling member adapted to engage with a drive shaft coupling member such that rotation of the drive shaft causes rotation of the capstan about a drive axis concentric with the bore and the drive shaft, and further adapted to disengage from the drive shaft coupling member such that rotation of the drive shaft does not cause rotation of capstan; and
 a plurality of tendons, each of the plurality of tendons including a proximal section coupled to one of the plurality of capstans and configured to wind around the capstan and including a distal section coupled to a member disposed at the distal end of the flexible tubular shaft.
11. The teleoperational instrument assembly of claim 10, wherein drive shafts of the plurality of drive motors extend in parallel to each other.
12. The teleoperational instrument assembly of claim 10, wherein drive shafts of the plurality of drive motors are

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- arranged in a plurality of rows extending from a base member of the teleoperational manipulator.
13. The teleoperational instrument assembly of claim 10, wherein the capstan coupling member is a projection and the drive shaft coupling member is a slot.
14. The teleoperational instrument assembly of claim 10, wherein the drive shaft coupling member is a projection and the capstan coupling member is a slot.
15. The teleoperational instrument assembly of claim 10, wherein the plurality of capstans includes a plurality of rows of capstans.
16. The teleoperational instrument assembly of claim 10, wherein each capstan of the plurality of capstans has a single engaging orientation with respect to the respective drive shaft of the teleoperational manipulator.
17. The teleoperational instrument assembly of claim 10, wherein each capstan of the plurality of capstans is arranged in parallel alignment with each of the other capstans in the plurality of capstans.
18. The teleoperational instrument assembly of claim 10, wherein each tendon of the plurality of tendons extends through a sheath inside the tubular shaft.
19. The teleoperational instrument assembly of claim 10, wherein the drive axis is perpendicular to the proximal end of the flexible tubular shaft.
20. The teleoperational instrument assembly of claim 10, wherein the mechanism engages the plurality of drive motors through a sterile barrier.

* * * * *

UNITED STATES PATENT AND TRADEMARK OFFICE
CERTIFICATE OF CORRECTION

PATENT NO. : 10,772,690 B2
APPLICATION NO. : 16/026673
DATED : September 15, 2020
INVENTOR(S) : Giuseppe M. Prisco

Page 1 of 1

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

On the Title Page

Item (57), Lines 1-8, The Abstract should read as:

-- A teleoperational instrument system includes a flexible tubular shaft; a mechanism coupled to the proximal end of the flexible tubular shaft, and a plurality of tendons. The mechanism includes a plurality of capstans, each including: a bore sized for concentric engagement with a drive shaft of a respective drive motor configured to drive the capstan; and a capstan coupling member adapted to engage with a drive shaft coupling member so rotation of the drive shaft causes rotation of the capstan about a drive axis. The capstan coupling member is adapted to disengage from the drive shaft coupling member so rotation of the drive shaft does not cause rotation of the capstan. Each of the plurality of tendons includes a proximal section coupled to one of the plurality of capstans and a distal section coupled to a member disposed at the distal end of the flexible tubular shaft. --

In the Specification

Column 1, Lines 7-13, under Cross-Reference to Related Applications should read as follows:

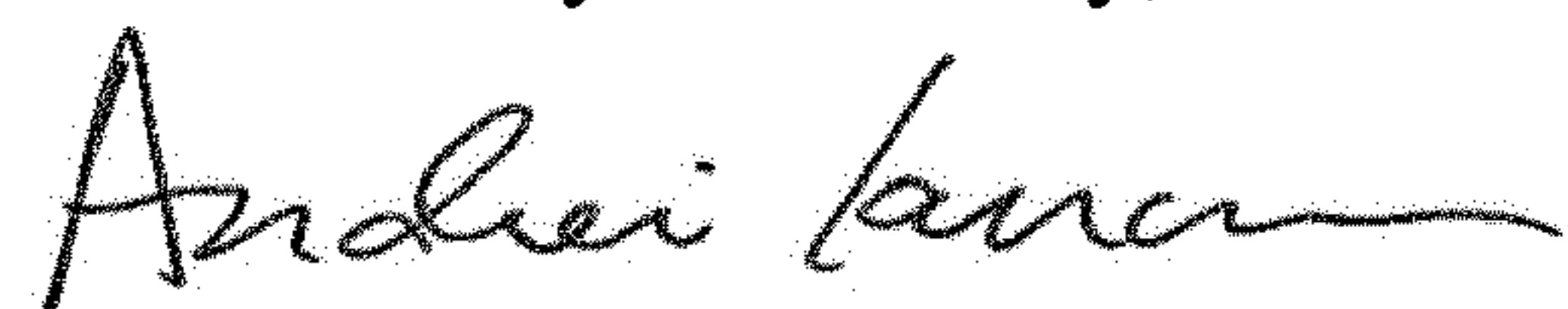
-- This application is a continuation application of U.S. Application No. 15/001,948, filed January 20, 2016, which is a continuation application of U.S. Application No. 12/286,644, filed September 30, 2008, and issued as U.S. Pat. No. 9,259,274, on February 16, 2016, both of which are incorporated herein by reference in their entireties. --

In the Claims

Column 14, Lines 20-22, Claim 18 should read:

-- The teleoperational instrument assembly of claim 10, wherein each tendon of the plurality of tendons extends through a sheath inside the flexible tubular shaft. --

Signed and Sealed this
Fifth Day of January, 2021



Andrei Iancu
Director of the United States Patent and Trademark Office